RTCA, Inc.
1828 L Street, NW, Suite 805
Washington, D.C. 20036-5133 USA

Assessment of Radio Frequency Interference Relevant to the GNSS L5/E5A Frequency Band

RTCA DO-292
July 29, 2004

Prepared by: SC-159
© 2004 RTCA, Inc.

Copies of this document may be obtained from

RTCA, Inc.

Telephone: 202-833-9339
Facsimile: 202-833-9434
Internet: www.rtca.org

Please visit the RTCA Online Store for document pricing and ordering information.

FOREWORD

This report was prepared by Special Committee 159 (SC-159) and approved by the RTCA Program Management Committee (PMC) on July 29, 2004.

RTCA, Incorporated is a not-for-profit corporation formed to advance the art and science of aviation and aviation electronic systems for the benefit of the public. The organization functions as a Federal Advisory Committee and develops consensus based recommendations on contemporary aviation issues. RTCA's objectives include but are not limited to:

- Coalescing aviation system user and provider technical requirements in a manner that helps government and industry meet their mutual objectives and responsibilities;

- Analyzing and recommending solutions to the system technical issues that aviation faces as it continues to pursue increased safety, system capacity, and efficiency;

- Developing consensus on the application of pertinent technology to fulfill user and provider requirements, including development of minimum operational performance standards for electronic systems and equipment that support aviation; and

- Assisting in developing the appropriate technical material upon which positions for the International Civil Aviation Organization and the International Telecommunication Union and other appropriate international organizations can be based.

The organizations' recommendations are often used as the basis for government and private sector decisions as well as the foundation for many Federal Aviation Administration Technical Standard Orders.

Since RTCA is not an official agency of the United States Government, its recommendations may not be regarded as statements of official government policy unless so enunciated by the U.S. government organization or agency having statutory jurisdiction over any matters to which the recommendations relate.

TABLE OF CONTENTS

1 INTRODUCTION 1

1.1 Background 1

1.2 Terms of Reference 2

1.3 Report Objectives 3

1.4 Report Organization 3

1.5 References 5

2 METHODOLOGIES OF AERONAUTICAL RFI SCENARIOS, RISK MODELING AND RFI ANALYSIS 7

2.1 Introduction and Basic Methodology 7

2.2 Spectrum Management for Safety Services: Regulations and Definitions 7

2.2.1 Relevant Definitions and Regulations in the ITU Radio Regulations 8

2.2.2 Relevant Definitions and Regulations in 47 CFR (FCC) 10

2.2.3 Description and Regulatory Status of L5/E5 Allocation 10

2.3 Aeronautical System Risk Analysis with RFI Effects 11

2.3.1 Process Overview 11

2.3.1.1 Target Level of Safety 11

2.3.1.2 Hazard Analysis and Risk Allocation 12

2.3.1.3 Threat Risk and Occurrence Rate Considerations 12

2.3.2 System Considerations for Approach and Landing 13

2.3.2.1 Total System Error and Its Components 13

2.3.2.2 Obstacle Clearance Surface (OCS) 13

2.3.2.3 NSE and FTE Impact on RFI Encounter Scenarios 14

2.3.2.4 Approach and Landing NSE and GPS Monitor Considerations 14

2.3.3 System Considerations for GNSS Signal Acquisition 14

2.4 Navigation System Performance and RFI 15

2.4.1 Description of Navigation System Performance 15

2.4.2 Effects of RFI on Navigation System Performance 16

2.4.3 Current Status of RFI Navigation Alerts and GPS Continuity and Integrity Risk Allocations 17

2.5 GPS Receiver Model for Performance and RFI Susceptibility Assessment 17

2.5.1 Antenna Gain 17

2.5.2 RF Front-end Frequency-Dependent Rejection 19

2.5.3 Maximum Receiver System Input Thermal Noise Density 19

2.5.4 Pulse Blanking 20

2.5.5 Receiver Effective Carrier -to-Noise Density Ratio (C/N0, EFF) Thresholds 21

2.6 Methodology for Aeronautical RFI Encounter Scenarios 22

2.6.1 Overview of Link Analysis Methodology 22

2.6.2 RFI Source Emissions and Effects Analysis 22

2.6.2.1 RFI Source Spectral Types 22

2.6.2.2 External RFI Emitter Classes 23

2.6.2.3 Effective Carrier-to-Noise Density Calculation Algorithm 24

2.6.3 Aeronautical Safety Margin 26

2.6.4 RFI Scenario Link Budget Templates 27

2.6.4.1 Link Budget Template Approach 27

2.6.4.2 Rationale for Two Allotments 28

2.6.4.3 Link Budget Templates Details and Rationale 29

2.7 Summary 31
2.8 References 31
3 AERONAUTICAL RFI ENCOUNTER SCENARIOS 33
3.1 Enroute Scenario 34
3.2 Transition to Final Approach Scenario 34
3.3 Non-Precision Approach with GNSS Guidance Scenario 34
3.4 Category I Precision Approach RFI Encounter Scenario 37
3.5 Category II/III Precision Approach RFI Scenario 38
3.5.1 Category II Vertical Flight Technical Error Considerations 38
3.5.2 Category II Vertical Encounter Minimum Separation Distance 39
3.5.3 Category III Vertical and Lateral RFI Encounter Considerations 40
3.6 Surface Movement Guidance RFI Encounter Scenarios 41
3.6.1 Taxiway Encounter Geometry 41
3.6.2 TSE Allowance for Continuity 42
3.7 Missed Approach 43
3.8 Take-Off 44
3.9 GPS Non-Precision Approach To 720ft HAT 46
3.10 Summary 46
3.10 Summary 47
3.11 References 47
4 GPS INTRASYSTEM AND GNSS INTERSYSTEM INTERFERENCE 49
4.1 Intrasystem and Intersystem Interference 49
4.2 Intrasystem Interference Characteristics 49
4.3 Effective Noise Density $N_{0,EFF}$ 50
4.4 Spectral Separation Coefficient Calculation 50
4.5 Computation Methodology 51
4.6 Intrasystem and Intersystem L5/E5A Interference Numerology 53
5 INTERFERENCE FROM ONBOARD ELECTRONICS 55
5.1 Introduction 55
5.2 VHF Air-Ground Transceivers (Including ACARS) 55
5.3 VHF Navigation Receivers 57
5.3.1 VHF Omni-directional Range (VOR) Receivers 57
5.3.2 VHF Instrument Landing System (ILS) Receivers 58
5.4 Emergency Locator Transmitters (ELTs) 58
5.5 High Frequency (HF) Transceivers 59
5.6 Distance Measuring Equipment (DME) 59
5.7 Pulsed Surveillance and Weather Radar Transmitters 61
5.7.1 ATCRBS 62
5.7.2 Mode S 62
5.7.3 TCAS 62

5.7.4 Automatic Dependent Surveillance – Broadcast (ADS-B) 63
5.7.5 Airborne Weather Radar 63
5.7.6 Overall Impact of Airborne Pulsed Systems 63
5.8 Mobile Satellite Services (Aircraft to Space) 65
5.8.1 Geosynchronous Aeronautical Mobile Satellite Service 65
5.8.2 Next-Generation Satellite Systems 66
5.9 Air – Ground Radiotelephone 67
5.9.1 General Aviation Air-Ground Radiotelephone 67
5.9.2 Commercial Aviation Air-Ground Radiotelephone 67
5.9.3 Cordless Handsets 68
5.10 Portable Electronic Devices 68
5.10.1 PED Emission Characteristics 68
5.10.2 PED-to-GPS Antenna Coupling Characteristics 69
5.10.3 Aggregate RFI Emissions Factor for PEDs 70
5.10.4 Aggregate On-board PED RFI Impact 70
5.11 References 71
6 FIXED AERONAUTICAL EMITTERS 73
6.1 VHF Ground Communications Transmitters 73
6.1.1 Overview 73
6.1.2 Aircraft Communications Addressing and Reporting System (ACARS) 74
6.1.3 VHF Air Traffic Control Communications 74
6.1.4 Harmonics from 118.0 – 137.0 MHz Ground-to Air Communications 75
6.1.5 VDL-3 (NEXCOM) 75
6.1.6 VDL-4 75
6.2 VHF Navigation Systems 76
6.2.1 VHF Omni-directional Range (VOR) Transmitters 76
6.2.2 Instrument Landing System (ILS) Localizer Transmitters 76
6.2.3 Local Area Augmentation System (LAAS) VHF Data Broadcast Transmitter 76
6.3 UHF Communications 77
6.4 Distance Measuring Equipment /TACAN (DME/T) 77
6.5 Secondary Surveillance Radar Interrogators 78
6.7 References 78
7 INTERFERENCE FROM AVIONICS ON NEARBY AIRCRAFT 79
7.1 VHF Communications 79
7.2 UHF Air-Ground Transceivers 80
7.3 Distance Measuring Equipment/TACAN (DME/TACAN) 80
7.4 Other Pulsed Sources 80
7.5 Joint Tactical Information Distribution System 80
7.5.1 JTIDS/MIDS Signal Structure 81
7.5.2 Restrictions on JTIDS/MIDS Operation in the NAS 82
7.5.2.1 JTIDS/MIDS Transmission Monitoring 82
7.5.2.2 JTIDS/MIDS Time Slot Duty Factor 82
7.5.2.3 JTIDS/MIDS Spectrum 84
7.6 Aeronautical Mobile Satellite Service 85
7.7 Next-Generation Satellite Systems 85

7.8 Airport Surface RFI Scenario and Link Calculations 85
8 COMMERCIAL BROADCAST SERVICES 87
8.1 AM Radio 87
8.2 FM Radio 87
8.3 Television 88
8.3.1 Analog Television 88
8.3.2 Digital Television 90
8.3.3 European Television 91
8.4 References 91
9 OTHER FIXED AND MOBILE INTERFERENCE SOURCES 93
9.1 Amateur Radio 93
9.2 Military Radar 94
9.3 JTIDS/MIDS Ground Equipment 95
9.3.1 US Army Ground Equipment 95
9.3.2 US Navy Ground Equipment 95
9.3.3 US Marine Corps Ground Equipment 96
9.3.4 US Air Force Platforms 96
9.4 VHF/UHF Fixed and Mobile Services 96
9.5 Wireless LAN Devices 97
9.6 Cellular Telephony 98
9.7 Cordless Telephony 98
9.7.1 Illicit Cordless Telephone Systems 99
9.8 Personal Radio Services 99
9.9 Ultra-Wideband (UWB) Systems 100
9.9.1 UWB Technology Overview 100
9.9.2 Review of Major UWB RFI Susceptibility Test and Analysis Activities 101
9.9.3 Current UWB Regulatory Status 102
9.9.3.1 UWB System Classifications 102
9.9.3.2 Operational Limitations 104
9.10 References 107
10 COMPOSITE PULSED RFI EFFECTS ON HIGH ALTITUDE OPERATIONS 109
10.1 Overall Composite RFI Scenario Analysis Methodology 109
10.1.1 Receiver Pulse Blanking, Filtering, and System Noise Assumptions 109
10.1.2 Theoretical Pulse Blanking Effects on Post-Correlation C/N0 110
10.2 Pulsed RFI Source Configurations, Assumptions, and Component Contributions 112
10.2.1 JTIDS/MIDS 112
10.2.1.1 JTIDS/MIDS Approach and Assumptions 113
10.2.1.2 JTIDS/MIDS RFI Parameter Results 114
10.2.2 1030/1090 MHz Surveillance Systems 114
10.2.2.1 Surveillance Systems Approach 115
10.2.2.2 Surveillance System RFI Parameter Results 115
10.2.3 DME/TACAN Interrogators On-board and on Nearby Aircraft 116
10.2.3.1 DME/TACAN Interrogator RFI Analysis Overview 116
10.2.3.2 DME/TACAN Interrogator RFI Effect Computation 117
10.2.4 DME/TACAN Ground Beacons 117

10.2.4.1 DME/TACAN Beacon Overview and General Approach 117
10.2.4.2 Rectangular Equivalent Pulse Width 120
10.2.4.3 Strong Pulse Collision Model - Net PDCb Approach for TACAN/DME RFI 122
10.2.4.4 Diffraction Loss Allowance for Beyond-Radio-LOS Beacons 124
10.2.4.5 DME/TACAN Beacon Component RFI Parameters for Worst-Case US Location 125
10.3 Composite Pulse RFI Effects on High Altitude Operations 126
10.3.1 High Altitude RFI Scenario Description 126
10.3.2 High Altitude Re-start Acquisition Analysis Strategy #1 127
10.3.3 High Altitude Re-start Acquisition Analysis Strategy #2 128
10.3.4 High Altitude Scenario RFI Link Analyses 129
10.3.4.1 High Altitude Re-start Acquisition RFI Link Analysis 129
10.3.4.2 High Altitude Enroute Tracking/Demod RFI Link Analysis 130
10.3.4.3 High Altitude Enroute Tracking Link Analysis with On-board PEDs RFI 132
10.4 Composite Pulse /Broadband RFI Effects on Transition Altitude Operations 133
10.4.1 Transition Altitude Scenario Detailed Description 133
10.4.2 Transition Altitude Scenario RFI Link Analysis Results 136
10.5 Conclusions and Recommendations 137
10.6 References 138
11 COMPOSITE PULSE/BROADBAND RFI EFFECTS ON APPROACH, TAKE-OFF, AND SURFACE MOVEMENT 141
11.1 MSS (Earth-to-Space) Mobile Earth Terminals 141
11.2 Ancillary Terrestrial Component (MSS) Repeaters 142
11.3 Composite L5 Broadband / Pulse RFI Environment for Approach, Take-off, and Surface Movement Scenarios 144
11.4 Approach, Take-off and Surface Movement Link Budget Calculations 145
11.4.1 Intentional Unlicensed In-band RFI EIRP 147
11.4.2 Surface Movement Separation Distance Derivation 150
11.5 LAAS and WAAS Scenario Issues 151
11.6 Recommendations 152
11.7 References 152
12 ADDITIONAL POTENTIAL INTERFERENCE SOURCES 155
12.1 Unintentional Emitters 155
12.2 Incidental RFI Emissions 155
12.3 Malfunctioning FCC-Licensed Equipment 156
12.4 Interference to GPS 157
12.5 Recommendations 158
12.6 References 159
13 MITIGATION TECHNIQUES FOR SIGNIFICANT SOURCES OF RFI 161
13.1 Interference Mitigation at the Source 161
13.1.1 Regulatory Control of Emissions 161
13.1.2 Identification and Localization of Interfering Sources 163
13.1.3 Mitigation of Interference Sources Aboard the Aircraft 164
13.1.4 Maintenance of an Incident Data Base 164

13.2 GPS Receiver Susceptibility Reduction 164
13.2.1 Adaptive Spatial (Antenna) Processing 164
13.2.2 Adaptive Temporal Filtering 165
13.2.3 Preselection 166
13.2.4 Improved Receiver Tracking Processes 166
13.2.5 Multibit Analog-to-Digital (A/D) Converters 166
13.2.6 Pulse Blanking 167
13.3 Mitigation at the Navigation System Architecture Level 167
13.3.1 Use of an Independent Conventional Navigation System 167
13.3.2 Use of Multiple Satellite Systems 167
13.3.3 Use of Multi-Frequency GNSS Receivers 168
13.4 Operational Constraints 168
13.5 References 168
14 CONCLUSIONS AND RECOMMENDATIONS 171
14.1 Summary Overview 171
14.2 Status of Recommendations from RTCA/DO-235A applicable to GNSS L5/E5A 172
14.3 Assessment Element Summaries 173
14.3.1 Aeronautical Navigation System Requirements and Analysis Methodology 173
14.3.2 Aeronautical RFI Encounter Scenario Development 174
14.3.3 Aeronautical RFI Source Assessments 175
14.3.3.1 GNSS L5/E5a Intra-system and Inter-system Interference 175
14.3.3.2 Interference from Onboard Electronic Equipment 175
14.3.3.3 Fixed Aeronautical Emitters 176
14.3.3.4 Interference from Avionics on Nearby Aircraft 176
14.3.3.5 Commercial Broadcast Service Emitters 176
14.3.3.6 Other Fixed and Mobile Interference Sources 176
14.3.3.7 Additional Interference Sources 177
14.3.3.8 Composite Pulsed RFI Effects on High Altitude L5 Operations 177
14.3.3.9 Composite Pulsed/Broadband RFI Effects on L5 Approach, Take-off, and Surface Operations 177
14.3.4 Mitigation Techniques for Significant RFI Sources 178
14.4 Recommendations 178
MEMBERSHIP 181

TABLE OF FIGURES

Figure 2-1 Measured L5 Receive Antenna Gain and Proposed Limits 18
Figure 2-2 Receiver Frequency-Dependent Rejection vs. Offset from L5 19
Figure 2-3 Block Diagram of a Typical Digital Pulse Blanking Receiver 20
Figure 2-4 Flow Chart for GNSS L5 RFI Source Composite 23
Figure 2-5 $N_{0.EFF}$ Algorithm Block Diagram 26
Figure 3-1 Non-Precision Approach Geometry (Side View) 35
Figure 3-2 Category I Scenario 37
Figure 3-3 Category II/III Approach Geometry 39
Figure 3-4 Airport Runway Protection Zones - Top View 40
Figure 3-5 Taxiway RFI Encounter Geometry - Front View 42
Figure 3-6 Surface Movement Guidance Separation Distance Diagram 43
Figure 3-7 Missed Approach Scenario Geometry 44
Figure 3-8 Take-off Scenario Geometry 45
Figure 5-1 Standard DME/TACAN Channel Plan 60

Figure 6-1 ACARS Hardware Emission Spectrum 74
Figure 6-2 ATC VHF Harmonic Emission Spectrum 75
Figure 7-1 JTIDS/MIDS Time Slot and Pulse Transmission Structure 81
Figure 7-2 JTIDS/MIDS Hopping Frequencies 82
Figure 7-3 JTIDS/MIDS Geographic Area Pulse Densities 83
Figure 7-4 JTIDS/MIDS Pulse Spectral Mask 84
Figure 7-5 JTIDS/MIDS Pulse Measured Spectrum 85
Figure 8-1 FM Broadcast Harmonic Emission Spectrum 88
Figure 8-2 Broadcast TV Harmonic Emission Spectrum 89
Figure 10-1 Typical DME/TACAN Antenna Normalized Gain vs. Elevation Angle 119
Figure 10-2 DME/TACAN Beacons Around Harrisburg, PA 119
Figure 10-3 Rectangular Equivalent Pulse Width of a Weak Pulse 121
Figure 10-4 Strong Pulsewidth and Residual Equivalent Pulsewidth vs. Peak Received Power with −90 dBm Pulse Blanking Threshold 122
Figure 10-5 Effect of Diffraction in Extending Propagation Path 124
Figure 10-6 DME/TACAN Beacon $N_{0,eff}$ Degradation Factor Contours at FL400 126
Figure 10-7 Overall $N_{0,EFF}$ Degradation Factor Contours in CONUS at FL400 132
Figure 10-8 In-Band TACANs within the RLOS in the vicinity of DCA 134
Figure 10-9 DCA Runway 4 Approach Plate 135
Figure 11-1 Take-off Scenario L5 RFI Link Budget Flow Chart 145

TABLE OF TABLES

Table 2-1 LAAS/WAAS Navigation System Performance Specifications 16
Table 2-2 Key L5 User Antenna Gain Values Used in the RFI Analyses 18
Table 2-3 Typical L5 Receiver System Noise Budget 19
Table 2-4 GPS and WAAS Tracking and Demodulation Thresholds 21
Table 2-5 GPS L5 Acquisition Thresholds for 1 ms Correlations 21
Table 2-6 Template for Approach, Take-off, and Surface Movement Scenarios 29
Table 2-7 High Altitude $C/N_{0,eff}$ Acquisition Link Budget Template 30
Table 3-1 Taxiway Obstacle Free Zones 41
Table 3-2 Separation Distance Calculation For Take-off Scenario 46
Table 3-3 Aeronautical RFI Encounter Scenario Parameters 47
Table 4-1 Aviation Receiver RFI Parameters for L5 Intrasystem Interference 54
Table 4-2 Aviation Receiver RFI Parameters for E5A Intersystem Interference 54
Table 5-1 VHF Channels with Harmonics at L5±10 MHz 57
Table 5-2 ELT Characteristics 58
Table 5-3 Aircraft Effective Isotropic Radiated Power (EIRP) 66
Table 5-4 Measured PED Emissions in the GPS L1 and L5 Bands and Applicable Standards 69
Table 6-1 Potential Interference from VHF Aeronautical Mobile Service 75
Table 8-1 Proximity of TV Carrier Harmonics to GPS L5 Band 89
Table 9-1 Amateur Radio Bands with Harmonics in GNSS L5 Band 93
Table 9-2 Other Amateur Bands Having Potential to Interfere with GNSS 93
Table 9-3 Land Mobile Frequency Bands 96
Table 9-4 Current Cellular Telephone Systems (824-894 MHz) 98
Table 9-5 Standardized Cordless Telephone Systems 99
Table 9-6 Bands used by the various Personal Radio Services 100
Table 10-1 JTIDS/MIDS Factors 114
Table 10-2 ATC RFI Results 116
Table 10-3 DME/TACAN Pulse RFI Parameters Near the Harrisburg Hot-Spot 125
Table 10-4 High Altitude Scenario Pulsed RFI Composite Parameters 127
Table 10-5 High Altitude GPS Acquisition $C/N_{0,EFF}$ Link Budget (Strategy #1) 130
Table 10-6 High Altitude $C/N_{0,EFF}$ Acquisition Link Budget (Strategy #2) 130
Table 10-7 Tracking / Data Demodulation $C/N_{0,eff}$ Link Budget 131

Table 10-8 In-band TACAN Beacons Near DCA 133
Table 10-9 Composite Pulsed RFI Parameters at Teple FAF (1600' MSL) 134
Table 10-10 Teple FAF GPS Acquisition $C/N_{0,\,eff}$ Link Budget 136
Table 10-11 Teple FAF Tracking / Data Demodulation $C/N_{0,\,eff}$ Link Budget 137
Table 11-1 $N_{0.EFF}$ Algorithm Input Parameters For All 7 Scenarios 144
Table 11-2 I_{0WBX} and $I_{0INBAND}$ EIRP Link budget Template for LAAS Approach, Take-off, Missed Approach and NPA Scenarios 148
Table 11-3 I_{0WBX} and $I_{0INBAND}$ EIRP Link budget Template for LAAS Approach, and Aircraft Surface Movement Scenarios 149
Table 11-4 I_{0WBX} and $I_{0INBAND}$ EIRP Link budget Template for WAAS Approach, and Take-off Scenarios 150
Table 11-5 RFI Performance Summary of the 7 Scenarios (4 Emitters) 152
Table 14-1 Aeronautical RFI Encounter Scenario Parameters 174

APPENDICES

APPENDIX A 193

A Total System Error Statistics For Precision Approach and Landings 195
A.1 Category II Operations 195
A.1.1 Category II Flight Technical Error Background 195
A.1.2 Navigation System Error Background and Calculations 196
A.1.3 Total System Error Calculation 197
A.1.4 Recommendation 197
A.2 Category I Operations 199
A.2.1 Category I FTE Background and Calculations 199
A.2.2 NSE Background and Calculations 200
A.2.3 TSE Background and Calculations 200
A.2.4 Recommendation 200
A.3 References 204

APPENDIX B 205

B RFI Source Specifications 207

APPENDIX C 211

C GPS L5 SIGNAL STRUCTURE AND EFFECTS OF NARROWBAND INTERFERENCE 213
C.1 GPS L5 Signal Structure 213
C.1.1 L5 Signal Characteristics 213
C.1.1.1 PRN Code Structure 214
C.1.1.2 Code Generation 214
C.1.1.3 Q5 Synchronization Sequence 215
C.1.2 Navigation Data 216
C.1.2.1 Navigation Data Modulation 216
C.1.2.1.1 Forward Error Correction 216
C.1.2.1.2 I-Component Neuman-Hoffman Code 216
C.1.3 User-Received Signal Levels 216
C.1.3.1 Supporting Material 217
C.2 L5 GPS Code Power Spectrum 217
C.3 Effects of CW Interference 221
C.3.1 CW Interference Effects on Signal Acquisition 222
C.3.2 CW Interference Effects on Signal Tracking 222
C.3.2.1 Detailed Derivation of the Effects of CW Interference 224
C.3.2.1.1 Effects of CW Interference On L5 Q-Code Tracking 225
C.3.2.1.2 Effects of CW Interference on Carrier Tracking 227

C.3.3 GPS Receiver Susceptibility to Non-CW Narrowband Interference 228
C.4 References 233

APPENDIX D 235

D MAXIMUM TOLERABLE INTERFERENCE ENVIRONMENT 237
D.1 $C/N_{0,EFF}$ Thresholds - Theoretical 237
D.1.1 Receiver Model 237
D.1.2 Acquisition 238
D.1.3 Acquisition of Rising Satellites 244
D.1.4 GPS Code and Carrier Tracking 245
D.1.5 GPS Data Demodulation 246
D.1.6 C/N_0 Thresholds - Simulations 246
D.2 Receiver Pulse Blanking and Saturation Effects on C/N_0 247
D.2.1 Effective C/N_0 for a Receiver Employing Pulse Blanking 247
D.2.2 Receiver Saturation Impact on Effective C/N0 250
D.2.3 Influence of Selectivity and Gain Distribution on Receiver Saturation and Blanking 251
D.3 Sensitivity of $C/N_{0,EFF}$ to the Pulse Blanking Threshold 253
D.4 Estimation of Aggregate Intra-system/ Intersystem Interference Power 257
D.4.1 Aggregate RFI Power Estimation Approach 257
D.4.2 Simulation Description 257
D.4.3 Simulation Results 260
D.5 Elevation Angle and C/N_0 Probabilities for Satellite Acquisition 261
D.5.1 Probability of Satellite Acquisition 262
D.5.2 Satellite Geometry Scenarios 262
D.5.3 C/N_0 Probabilities 264
D.6 RFI Effects on High Altitude Operations over the European Hot-Spot 267
D.7 References 268

APPENDIX E 271

E Receiver RFI Performance: Analysis/ Simulation/ Emulation 273
E.1 Detailed Derivation of ATC/ Surveillance System RFI Parameters 273
E.1.1 Background Emitter Distributions 274
E.1.2 Link Equations for Ground and Airborne Emitters 276
E.1.3 Pulsed Duty Factor Assumptions 278
E.1.3.1 ATCRBS and Mode S Sensors 278
E.1.3.2 ATCRBS and Mode S Transponders 278
E.1.3.3 1090 MHz Extended Squitter System 279
E.1.3.4 Traffic Alert and Collision Avoidance System 279
E.1.4 Surveillance System RFI Analysis 280
E.2 On-Board Pulsed RFI Transient and Steady-State Analysis 282
E.2.1 GNSS Active Antenna Unit Preselector Steady-State Frequency Domain Analysis 282
E.2.1.1 Antenna Unit Preselector and Low Noise Preamplifier Performance Aspects 282
E.2.1.2 Preselector Circuit Synthesis 283
E.2.1.3 Preselector Circuit Steady-State Frequency Response Computation 284
E.2.2 GNSS Active Antenna Unit Preselector Time Domain Analysis 285
E.2.2.1 DME and Surveillance Transmit Pulse Envelope Model 285
E.2.2.2 Airborne Antenna Coupling and Thevenin Equivalent Pulse Source Model 285
E.2.2.3 Preselector Time Domain Response Computation 286
E.2.3 Steady-State and Transient Response Results Summary and Conclusions 288
E.3 On-Board PEDs Aggregate Emission Analysis 289
E.3.1 PED Emission Considerations 289
E.3.2 PED Interference Propagation Loss Considerations 291
E.3.3 Aggregate PED RFI Emission Computation for Boeing 737-200 293
E.4 Propagation Modeling with the GPS RFI Environmental Evaluation Tool (GREET) 295

E.4.1 Fixed Emitter Database Interface 296
E.4.2 Fixed Emitter RFI Calculator 297
E.4.3 Emulation of DME/TACAN Ensemble Environment 298
E.5 Monte Carlo Analysis of the PDCb Blanking Model for TACAN/DME RFI 302
E.6 Hardware Prototype L5 Receiver Bench Tests 308
E.6.1 JTIDS/MIDS Environments 309
E.6.2 Test Configuration 309
E.6.3 Digital Pulse Blanker Soft Threshold 314
E.7 References 315

APPENDIX F 317

F STANDARD TEST INTERFERENCE ENVIRONMENT 319
F.1 Introduction 319
F.2 Desired Signal Levels 319
F.3 Stress-Case Continuous Interference Environment 320
F.4 Stress-Case Pulsed Interference 322

APPENDIX G 325

G INSTALLED AIRCRAFT GNSS ANTENNA PARAMETERS 327
G.1 Introduction 327
G.2 Frequency Response 327
G.3 Antenna Gain Pattern 327
G.3.1 Simulation 328
G.3.2 Full Scale Fuselage Section Tests 329
G.3.3 Scale Model Measurements 330
G.3.4 Antenna Gain Pattern Factor Discussion 330
G.4 Polarization Mismatch 331
G.5 Summary 331
G.6 References 332

APPENDIX H 341

H Interference from an Aggregation of Emitters 343
H.1 Introduction 343
H.2 Circular Geometry of Emitters 343
H.3 Rectangular Geometry of Emitters 346
H.3.1 Merging Discrete Emitter Model with a Continuum of Emitter Model 348
H.4 Analysis of Emitters at Random Locations 351
H.5 Interference Power at Receiver Front End 352
H.6 Conclusions 353
H.7 References 353

APPENDIX I 355

I Noise Equivalency Factor Measurement and Analysis Method 357

APPENDIX J 359

J EUROCAE WG62 RFI Effects Analysis at US and European Hot-Spots 361
J.1 Effective Post-Correlation Carrier-to-Noise Density Ratio Degradation Computation 361
J.2 DME/TACAN Beacon Component RFI Parameters for Worst-Case European Location 362
J.3 European Worst-case High Altitude Acquisition Link budget 367
J.4 US High altitude RFI Acquisition Scenario Description 367
J.5 US Worst-case High Altitude Acquisition Link budget 368
J.6 Summary 369
J.7 References 369

APPENDIX K 377

K ACRONYMS, ABBREVIATIONS, and DEFINITIONS 379
K.1 Acronyms and Abbreviations 379
K.2 Definitions 388

TABLE OF FIGURES

Figure A- 1 GBAS NSE Distribution Averaged over All Geometries that Meet VAL<10 Meters 197
Figure A- 2 Category II TSE Probability Density Function 198
Figure A- 3 Category II Cumulative TSE Probability Function 198
Figure A- 4 Truncated TSE Probability Density Function for Auto-coupled Aircraft 202
Figure A- 5 Truncated "Two-Tier" FTE Probability Density Function for Manual Approach Aircraft (σ_{FTE1} = 12.5 ft and σ_{FTE2} = 9ft) 203
Figure A- 6 Truncated TSE Probability Density Function for Manual Approach Aircraft 203

Figure C- 1 Generation of L5 Codes 215
Figure C- 2 Modulation of L5 Signals 215
Figure C- 3 Convolutional Encoder 216
Figure C- 4 Total Received L5 RF Signal Strength Versus Elevation Angle 217
Figure C- 5 1-kHz Spaced Line Spectrum for a Typical L5 Code 218
Figure C- 6 1-kHz Spaced Line Spectrum for a Typical L5 Code – Close-In 219
Figure C- 7 50-Hz Spaced Line Spectrum for a Typical L5 Code 220
Figure C- 8 50-Hz Spaced Line Spectrum for a Typical L5 Code – Close-In 221
Figure C- 9 CW Effect Phase Diagram 223
Figure C- 10 Correlation Peak Distortion Versus CW Interference (121.756-kHz) Phase, 1-Chip Spacing 225
Figure C- 11 DLL Discriminators with CW Interference 226
Figure C- 12 RMS Code Tracking Error with CW Interference at 121.746-kHz – 1-Chip Spacing 226
Figure C- 13 Carrier Phase Errors for Different Phases of CW Interference 228
Figure C- 14 Pre-Correlation Interference Power Relative to Total Interference Power in 20 MHz Bandwidth – Acquisition Case 230
Figure C- 15 Pre-Correlation Interference Power Relative to Total Interference Power in 20 MHz Bandwidth – Tracking Case 231
Figure C- 16 Pre-Correlation Interference Power Correction Factor – Acquisition Case 232
Figure C- 17 Pre-Correlation Interference Power Correction Factor – Tracking Case 233

Figure D- 1 GPS L5 Receiver Digital Channel Model 237
Figure D- 2 Acquisition Decision Statistic Generation for I5/Q5 Technique 239
Figure D- 3 Acquisition Decision Statistic Generation for Q5-only Technique 239
Figure D- 4 Max. Dwell Time vs. Number of Correlators (1-ms Integration) 242
Figure D- 5 Max. Dwell Time vs. Number of Correlators (20-ms Integration) 242
Figure D- 6 Minimum $C/N_{0,EFF}$ to Achieve 1-min Acquisition of the First Satellite 243
Figure D- 7 Minimum $C/N_{0,EFF}$ - Subsequent (2^{nd} – 4^{th}) Satellite Acquisition 244
Figure D- 8 Probability of Cycle-slips vs. $C/N_{0,EFF}$ 246
Figure D- 9 Monte-Carlo Simulation Results for L5 Carrier Phase Tracking and Data Demodulation 247
Figure D- 10 Correlator Model 248
Figure D- 11 Receiver Model Rejection Characteristics 252
Figure D- 12 Receiver Model Rejection Curve (12 dB/MHz Mask) 252
Figure D- 13 CONUS Hotspot RFI Parameters vs. Blanking Threshold 254
Figure D- 14 CONUS Hotspot Overall RFI Parameters vs. Blanking Threshold 255
Figure D- 15 European Hotspot Overall RFI Parameters vs. Blanking Threshold Ground DME/TACAN beacons, JTIDS Case 8/ 51, ATC/ARNS 257
Figure D- 16 GPS Satellite Antenna Pattern on L5 258
Figure D- 17 GPS L5 user Received Power 258

Figure D- 18 Galileo Satellite Antenna Pattern on E5A 259
Figure D- 19 Galileo E5A User Received Power 259
Figure D- 20 GPS Patch Antenna Gain Pattern on L5 260
Figure D- 21 Probability of Maximum Elevation Angle Given 2 Satellite Failures 263
Figure D- 22 Post-Correlation Interference-Free C/N_0 vs. Elevation Angle 264
Figure D- 23 $P_{C/N_0>X}$ for the Noise-Only Case 265
Figure D- 24 Expansion of $P_{C/N_0>X}$ for the Noise-Only Case at Lower X Values 266
Figure D- 25 Overall L5/E5a $N_{0,EFF}$ Degradation Contours at FL400 for Europe 268

Figure E- 1 Cumulative Number of Nodes Within x Grid Units 274
Figure E- 2 Grid Effect as a Function of Normalized Range 275
Figure E- 3 4-Resonator L5 Bandpass Preselector Filter Equivalent Circuit 283
Figure E- 4 L5 Preselector Equivalent Circuit Insertion Loss vs. Frequency 284
Figure E- 5 1150 MHz DME Input and BPF Output Pulses 287
Figure E- 6 1090 MHz ATCRBS Input and BPF Output Pulses 288
Figure E- 7 NASA Interference Propagation Loss Measurement Set-up Diagram 291
Figure E- 8 Interference Path Loss Measurements on Boeing 737-200 Aircraft 293
Figure E- 9 GREET Flow Diagram 296
Figure E- 10 Normalized DME/TACAN Complex Envelope obtained from Otis AFB, MA TACAN 299
Figure E- 11 Emulated DME/TACAN Environment: 40 kft above Harrisburg, PA. 300
Figure E- 12 Envelop of Two Overlapping Gaussian Pulses 303
Figure E- 13 Aggregate Inter-Arrival Distributions 304
Figure E- 14 Simulation Results for Uniform Pulse Width Distribution 306
Figure E- 15 Prototype Receiver Test Configurations Diagram 310
Figure E- 16 DPB Threshold Test 315

Figure F- 1 Stress-case Continuous Interference Levels at the Antenna Port 320
Figure F- 2 Stress-Case Continuous Interference Environments 321

Figure G- 1 Measured L5 Patch Antenna Elevation Pattern and Proposed L5 Limits 333
Figure G- 2 GTD Roll Plane Pattern Simulations 333
Figure G- 3 Antenna on Flat Ground Plane Figure G- 4 Antenna on 1.76m Cylinder (Beechjet) 334
Figure G- 5 Antenna on 2.83m Cylinder (Canadair) Figure G- 6 Antenna on 6.76m Cylinder (737) 334
Figure G- 7 Fuselage Section Pattern Measurement Orientations 335
Figure G- 8 Antenna 1 Pitch Axis Pattern Scan 336
Figure G- 9 Antenna 1 Roll Axis Pattern Scan 336
Figure G- 10 Antenna 2 Pitch Axis Pattern Scan 337
Figure G- 11 BAC 1-11 1/9 Scale Model Radiation Distribution Pattern 339
Figure G- 12 L1 Patch Antenna on a Flat Ground Plane – Polarization Response 339

Figure H- 1 Receiver-Emitter Geometry-Side View 344
Figure H- 2 Limitation of Emitters by Earth's Curvature 345
Figure H- 3 Total Power Plot for a Rectangular Continuum of Emitters, D=1 347
Figure H- 4 Square Enclosing Circle Enclosing a Square of Emitters 347
Figure H- 5 Geometry for Merging Discrete Emitters with Continuum Approximation 350
Figure H- 6 Example of Random Emitters in a City 351

Figure I- 1 Broadband Noise Normalization and Partial UWB Substitution Illustration 357
Figure I- 2 Broadband Noise Equivalency Factor Illustration 358

Figure J- 1 Considered DME/TACAN beacon antenna gains versus elevation 363
Figure J- 2 E5a/L5 effective post-correlation C/N0 degradation due to DME/TACAN beacons over Europe at FL400 – blanking threshold of -117.1 dBW 363

Figure J- 3 E5b effective post-correlation C/N0 degradation due to DME/TACAN beacons over Europe at FL400 – blanking threshold of -120.0 dBW 364
Figure J- 4 E5a/L5 effective post-correlation C/N_0 degradation due to DME/TACAN beacons over the US at FL400 – blanking threshold of -117.1 dBW 365
Figure J- 5 E5b effective post-correlation C/N_0 degradation due to DME/TACAN beacons over the US at FL400 – blanking threshold of -120.0 dBW European High altitude RFI Acquisition Scenario Description 365

TABLE OF TABLES

Table A- 1 Category I Average Geometry Probability Density Function 201
Table A- 2 Category I Average Geometry Probability Density Function 201
Table A- 3 Category I Average Geometry Probability Density Function 202

Table B- 1 Continuous Sources 207
Table B- 2 Pulsed Sources 208

Table C- 1 Received Minimum L5 RF Signal Strength 217

Table D- 1 LINE-OF-SIGHT VELOCITY UNCERTAINTY 240
Table D- 2 PDC_b and R_i Estimates of JTIDS/MIDS Case 8 per Blanking Threshold 256
Table D- 3 Aggregate power factors for L5 and E5A I or Q Components 261
Table D- 4 Satellite Failure Probabilities 263
Table D- 5 EU High Altitude Scenario Pulsed RFI Composite Parameters 267
Table D- 6 EU High Altitude GPS Acquisition $C/N_{0,\,eff}$ Link Budget 267

Table E- 1 SSR Interrogator Characteristics 277
Table E- 2 SSR Transponder Characteristics 277
Table E- 3 Summary Results – Generic Case 281
Table E- 4 Preselector Circuit Parameters at Selected Frequencies 285
Table E- 5 Representative Aircraft L-Band Antenna Coupling Factors 286
Table E- 6 Measured PED Emissions in the GPS L1 and L5 Bands 290
Table E- 7 Boeing 737-200 (#1883) PED Interference Path Losses to GPS Antenna 294
Table E- 8 GREET-Generated GPS L5-Interfering DME/TACANs at 40,000 ft Above Mean Sea Level (MSL) (* Type 1 = DME, Type 2= TACAN) 301
Table E- 9 Detailed Results Associated with Figure E- 14 306
Table E- 10 Blanking test for N = 20 TACAN Emitters 307
Table E- 11 JTIDS/TACAN DME Noise Reference Calculation and L5 Transmit Level 311
Table E- 12 L5 Degradation vs. JTIDS Environments and L_5 Carrier Levels 312
Table E- 13 L5 Degradation versus DME Frequency Location 313

Table F- 1 STRESS-CASE CONTINUOUS INTERFERENCE BANDWIDTH DEFINITIONS (GPS SIGNAL TRACKING) 322
Table F- 2 STRESS-CASE PULSED INTERFERENCE 323

Table H- 1 Total Power for the Geometries Shown in Figure H-4 348
Table H- 2 Power Density Comparison, Height = 100 m, Emitter Spacing = 100 m. 348
Table H- 3 Power Density Comparison, Height = 15 m, Emitter Spacing = 100 m. 349
Table H- 4 Power Density Comparison, Height = 100 m, Emitter Spacing = 25 m. 350
Table H- 5 Power Density Comparison, Height = 15 m, Emitter Spacing = 25 m. 350
Table H- 6 Total Power Density from Discrete Emitters at Random Locations 351
Table H- 7 Noise to L5 Receiver Front End from Aggregate Unwanted RFI 352
Table H- 8 Noise to L5 Receiver Front End from Aggregate Intentional Unlicensed In-band RFI 352

Table J- 1 E5a/L5 high altitude (FL 400) European hot-spot degradation due to DME/TACAN and JTIDS/MIDS systems – blanking threshold of -117.1 dBW 366
Table J- 2 E5b high altitude (FL 400) European hot-spot degradation due to DME/TACAN and JTIDS/MIDS systems – blanking threshold of -120.0 dBW 367
Table J- 3 Galileo E5a/E5b and GPS L5 high altitude acquisition scenario power link budget over the EU hot-spot 367
Table J- 4 E5a/L5 high altitude (FL 400) US hot-spot degradation due to DME/TACAN and JTIDS/MIDS systems – blanking threshold of -117.1 dBW 368
Table J- 5 E5b high altitude (FL 400) US hot-spot degradation due to DME/TACAN and JTIDS/MIDS systems – blanking threshold of -120.0 dBW 368
Table J- 6 Galileo E5a/E5b and GPS L5 high altitude acquisition scenario power link budget over the US hot-spot 368

1 INTRODUCTION

1.1 Background

The original GNSS L1 RFI environment assessment by RTCA (RTCA/DO-235), completed in late 1996, identified potential sources of RFI and assessed the vulnerability of GNSS receivers (particularly GPS) to that interference. The navigation signals considered were the GPS and GLONASS Standard Positioning Service (SPS) signals on their respective L1 carriers, and the L1 signals transmitted by the FAA Wide Area Augmentation System (WAAS). The original assessment was motivated by a number of factors. These included sporadic GPS interference trouble reports from various RFI sources, the potential RFI from new sources in adjacent frequency bands, and the need to identify appropriate mitigation measures for flight-critical GNSS applications. Out of the original assessment work came susceptibility requirements for RTCA/DO-229 GPS/WAAS airborne receiver standard, two proposals for “Big-LEO” Mobile Satellite Service transmitter emission requirements, and several other key findings.

In a November 1999, letter, the Department of Transportation (DOT) requested that RTCA to "continue to further the necessary work for L5 and determine appropriate susceptibility criterion and subsequent unwanted emission protection levels for this new GPS signal." The letter went on to say "We ask that the RTCA take on this task and devote a Working Group towards defining the appropriate unwanted emission protection levels and susceptibility criteria for L5. We request that such work be published in an RTCA report similar in nature to Assessment of Radio Frequency Interference Relevant to the GNSS, RTCA Report DO-235 of January 1997. In response, the RTCA undertook to investigate the RFI environment near the GPS L5 frequency (1176.45 ± 12 MHz), and determine appropriate receiver susceptibility criteria and related RFI unwanted emission limits for the use with new civil signal. ." In a June 2000 DOT letter, the DOT requested that RTCA "examine the issues of potential interference from ultra-wideband (UWB) technology to critical aviation systems, including the Global Positioning System (GPS)." It went on to say "We ask RTCA's assistance in developing appropriate operational scenarios for these systems. It suggested, "RTCA may wish to expand the charter of the current SC-159 WG6 to include this work for analysis of impacts at both L5 and L1." In a July 2000 letter to Mr. Joseph Canny, DOT, RTCA replied, "SC-159 is currently addressing Ultra Wide Band (UWB) interference issues for the L5 band and will now include the L1 band in its work. Recent SC-159 documents [1-1, -2, -3] addressed these issues pertaining to GNSS L1. This report addresses potential radio frequency interference to the future GPS L5 signal when used for aeronautical radionavigation, and includes RFI to the Galileo E5A signal as well, where feasible.

The frequency band for L5 was selected from a large number of candidates, because it has the most favorable characteristics: It is close enough in frequency to L1 and L2 that the GPS satellite can support it; it is separated from L1 sufficiently to provide all the benefits from a second signal; and it is allocated worldwide to the aeronautical radionavigation service (ARNS). This allocation status will provide GPS L5 with regulatory protection from interference that is not available in bands allocated to other services.

The potential sources of RFI to the GPS L5 signal are vastly more complicated than those for the L1 signal. For instance, L1 operates in a frequency band where the only signal, which is in-band to GPS, is GPS itself, plus its own augmentations. Unlike L1, the L5

© 2004 RTCA, Inc.

signal must contend with non-GPS ARNS signals, namely those transmitted by the distance measuring equipment (DME) ground based beacons. Also, the band supports the Joint Tactical Information Distribution System (JTIDS). DME and JTIDS signals are high power pulsed. Having said that, the potential interference from these systems was felt to be manageable for several reasons. First, because DME operation is controlled by the aviation authority; and JTIDS peacetime operation is controlled through coordination of peacetime operations with the aviation authority. Second because, it was felt that interference would be significant only at altitude.

The design of the L5 receiver incorporates mitigation techniques to deal with high and low power pulsed signals, but they do take a toll on its performance if the pulse density is high enough. Like L1, the L5 aviation receiver will encounter other signals from systems not in its frequency band, such as harmonics and spurious emissions from broadcast and land mobile systems. Then there are ultrawideband (UWB) systems, which transmit in the L5 frequency band. This report deals with all of the above environmental sources of interference, plus those that are onboard the same aircraft, including avionics and personal electronic devices (PEDS) that may be brought on-board by passengers, and crew.

1.2 Terms of Reference

SC-159 Working Group 6 was created to investigate radio-frequency interference issues, and appropriate mitigation alternatives, relevant to GNSS. The original Terms of Reference for this group were to:

a. Develop quantitative assessments of the current and projected RF interference (RFI) environment;

b. Recommend measures to reduce RFI at the source where it is technically feasible and cost-effective to do so;

c. Develop updated interference rejection criteria for future GNSS receivers that will enable them to satisfy required navigation performance in the near future RFI environment;

d. Develop an out-of-band emissions mask for adjacent-band Mobile Satellite System mobile Earth terminals.

In response to the November 1999 DOT letter cited above, the RTCA included in the Working Group 6 terms of reference a task to investigate environmental RFI interference to the new GPS L5. At the request of Eurocae, RTCA agreed to include an analysis of Galileo E5, as time allowed.

New terms were added in mid-2000 to address certain issues with UWB and other new RFI sources and proposed new operational uses. They are:

a. Develop RFI encounter scenarios for new aeronautical and non-aeronautical public safety operations with GPS receivers, review and revise current scenarios as required;

b. Assess the potential for RFI to GPS receivers from proposed unlicensed UWB transmitters and recommend suitable emission limits and other associated mitigations for use by the FAA and DOT in FCC rulemaking proceedings;

© 2004 RTCA, Inc.